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Techno-economic analysis of a natural gas combined cycle power plant integrated with a Ca-looping process for post-combustion capture

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Abstract

In this study, it was sought to find an efficient way to integrate a natural calcium oxide looping process with a Natural Gas Combined Cycle (NGCC) power plant for its post-combustion CO_2 capture. To achieve 90% carbon capture from the NGCC flue gases containing no more than 4.0 % CO_2, the carbonator should operate at a lower temperature than when it runs for a coal-fuelled power plant due to the thermodynamic limit of chemical reaction equilibrium of CO_2 with calcium oxide (CaO). In turn, the decreased carbonator temperature gives rise to 1) more solids circulating due to reduction of the CO_2 absorption rate and 2) more fuel consumption in the calciner for heating up the solids. To alleviate the adverse effects, it was proposed to implement exhaust gas recirculation (EGR) by which the CO_2 content could increase up to 6.8 %, enabling the NGCC to have a net power efficiency to an extent similar to ones integrated with amine capture. As a result of economic analysis of the capture cases, it was concluded that integrating a NGCC with a Ca-looping unit would be more lucrative than amine capture cases with respect to the cost of electricity (COE) and cost of CO_2 avoided (COA).

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Key words: Ca-looping, Exhaust gas recirculation, Natural Gas Combined Cycle, Economic analysis, Process simulation

1. Introduction

Global climate change caused by greenhouse gas emissions is the most serious environmental issue facing humanity in this century. The EU set out its plan to cut its greenhouse gas emissions by 80% by 2050 against the 1990 levels (EC Climate Action, 2011). Among various greenhouse gases, carbon dioxide

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accounts for around 80% of the total anthropogenic greenhouse gases and its emission amounted to approximately 35 billion tons per annum in 2011 (Olivier et al., 2013). Therefore, it is crucial to curtail the CO_2 emission substantially in order to achieve the target to limit global warming well below 2 °C above the pre-industrial levels agreed globally in 2015 Paris Agreement.

In particular, the CO_2 emission resulting from fossil fuel combustion for power generation accounts for almost 40% of the total anthropogenic CO_2 emission. Moreover, it is likely to see global electricity demand increase gradually up to 34,290 TWh in 2030 from 19,756 TWh in 2009. It is expected that around 20% of the total electricity production be still sourced by natural gas (IEA, 2009). Therefore, it is necessary to find the most efficient way to reduce the CO_2 emission at natural gas-fuelled power plants as well as coal-fuelled power plants.

Up to now, for large-scale post-combustion CO_2 capture, chemical solvent processes represented by amine capture processes are regarded as the most technically and economically feasible technology. However, integrating an amine capture plant using an aqueous monoethanolamine (MEA) solvent with a power plant would require huge amount of steam to be extracted from the steam cycle for solvent regeneration, in whichever way its process configuration was optimized (Ahn et al., 2013). Such a great energy penalty involved in amine capture plants has made it difficult to implement carbon capture and storage for decarbonizing fossil fuel-based power plants up to now. Therefore, it is necessary to develop an alternative capture process incurring less energy penalty than an amine capture plant in order to facilitate its commercialization.

A Calcium Oxide (CaO) looping process has attracted great attentions from researchers due to its potential to achieve a lower energy penalty than a MEA capture unit (Atsonios et al., 2015; Cormos, 2015; Ozcan et al., 2013). CaO circulates between two fluidized beds where CaO reacts selectively with CO_2 into $CaCO_3$ at the carbonator while the $CaCO_3$ is regenerated into CaO to produce pure CO_2 at the calciner. The heat of reaction for regenerating the $CaCO_3$ (4.1 MJ/kgCO_2) is larger than the specific heat duty at a MEA capture unit (3.7 MJ/kgCO_2). However, the heat consumed in the calciner can be partly recovered by way of generating steam, which paves a way to make it possible for a power plant to undergo less energy penalty. For example the heat of reaction generated at the carbonator should be recovered as steam in order to keep the reactor temperature constant at a desired set point. There are also several hot solid and gas streams available for additional heat recovery. The steam generated by recovering the heat can be utilised to produce additional power.

It is well known (DOE/NETL, 2013) that the CO_2 emission factor at a NGCC (364 kgCO_2/MWh) is less than 50% the CO_2 emission factor at a PC-fired power plant (800 kgCO_2/MWh). However, it is unlikely to be able to capture the CO_2 at a NGCC at the same efficiency as it is practised at a PC-fired power plant since the NGCC flue gas contains only 4% CO_2, in marked contrast to 15% at a PC-fired power plant. The energy penalty involved in CO_2 capture is by and large inversely proportional to the CO_2 concentration in the feed. To overcome adverse effects caused by such a low CO_2 level at NGCCs, several researchers trailed a new NGCC configuration in which part of the flue gas is recirculated and mixed with the air flowing to its gas cycle to increase the CO_2 content in the flue gas. More importantly, the volumetric flowrate of the flue gas unit will be reduced greatly by the exhaust gas recirculation (EGR).

Several studies have attempted to evaluate the performance of a NGCC integrated with a Ca-looping unit (Berstad et al., 2014). They concluded that a natural calcium oxide looping unit would perform worse than an MEA capture unit. However, they did not look closely into the effect of varying CO_2 concentrations in the feed on a Ca-looping unit. In this study, we determined operating conditions of a Ca-looping unit for achieving 90% CO2 capture given the CO_2 concentration in the flue gas at a NGCC in the first place and then conducted techno-economic analysis of a NGCC integrated with a Ca-looping unit in comparison to

ones integrated with a conventional amine process. The aim of this study is to quantify the effects of EGR on performance of a NGCC integrated with a Ca-looping unit.

2. Process description

2.1. NGCC power plant

An exemplary NGCC power plant was selected as base case of this study (DOE/NETL, 2013). The composition of a natural gas feed is 93.1% methane, 3.2% ethane, 0.7% propane, 0.4% n-butane, 1.0% CO_2 and 1.6% nitrogen in molar percentage. The natural gas combusts with compressed air at combustion chamber. Combustion gas expands at a gas turbine to generate the electricity of 374.5 MW_e. The performance of the gas cycle was estimated at the pressure ratio of 18.5 with the combustion gas flowing to the gas turbine at 1371 °C. Exhaust gas leaving the gas turbine passes through a heat recovery steam generator (HRSG) to generate superheated steams at three pressure levels. Each steam is connected to a steam turbine for generating additional 203.3 MW_e electricity.

2.2. Ca-looping process

Due to thermodynamic limitation of chemical reaction of CaO with CO_2, the carbonation temperature is usually set at 650 °C for 90% capture in case of 15 mol % CO_2 flue gases of coal-fired power plants (Alonso et al., 2009) and it must be lower than calcination temperature (950 °C). However, the carbonation temperature must be chosen as closely to calcination temperature as possible to save the energy consumption for heating up the circulating solids in a calciner. The maximum temperature of a carbonator is limited by the CO_2 partial pressure in a flue gas. In other words, the state of solid phase (CaO or $CaCO_3$) is more or less determined by chemical reaction equilibrium, being a function of temperature and CO_2 partial pressure as follows (Alonso et al., 2009).

$$f_e = \frac{10^{(7.079-8303/T)}}{p_{total}} \quad (1)$$

where f_e is CO_2 molar fraction at equilibrium; T is carbonation temperature, K; p_{total} is total pressure, atm. Eq.1 indicates that the carbonator temperature can be increased with increasing CO_2 partial pressure in the feed. A different set of F_R/F_{CO2} and F_0/F_{CO2} can be chosen to achieve the targeted 90% capture. It was assumed that the amount of CaO purge (and fresh $CaCO_3$ make-up) must be maintained as low as possible and chosen the same for the two cases, i.e. , i.e. non-EGR and 40% EGR. In this study, the F_0/F_{CO2} was fixed as 0.1. The operating conditions of a Ca-looping unit are listed in Table 1 for the two cases.

Table 1. Parameters of a Ca-looping process at 90% CO_2 capture.

Process configuration		Non-EGR case (4.0% CO_2)	40% EGR case (6.8% CO_2)
Natural $CaCO_3$ deactivation parameters	X_r	0.075	
	k	0.52	
Carbonator	Temperature [°C]	580	605
	F_R/F_{CO2}	14	7.6
	F_0/F_{CO2}	0.1	
Calciner	Efficiency [%]	100	

3. Case studies

It has been reported that a Ca-looping unit would be more economical than conventional amine processes for decarbonising a coal-fired power plant as long as good heat recovery was implemented. However, it is likely that a Ca-looping unit results in greater energy penalty when applied to a NGCC rather than a coal-fired power plant. Therefore, to see if a Ca-looping unit is worth investigating further as an alternative to amine processes for decarbonising a NGCC, it is essential to evaluate its process performance from a techno-economic perspective against the conventional amine process. In this study, an absorptive capture unit using aqueous 30 wt% MEA solvent integrated with the reference NGCC was simulated in order to set out a performance target. Below are all the cases investigated in this study along with figures depicting the overall process configuration.

- Base case: NGCC reference plant (DOE/NETL, 2013).
- Case 1: NGCC + MEA absorption unit , Fig. 1(a)
- Case 2: NGCC/40% EGR + MEA absorption unit, Fig. 1(b)
- Case 3: NGCC + Ca-looping unit, Fig. 1(c)
- Case 4: NGCC/40% EGR + Ca-looping unit, Fig. 1(d)

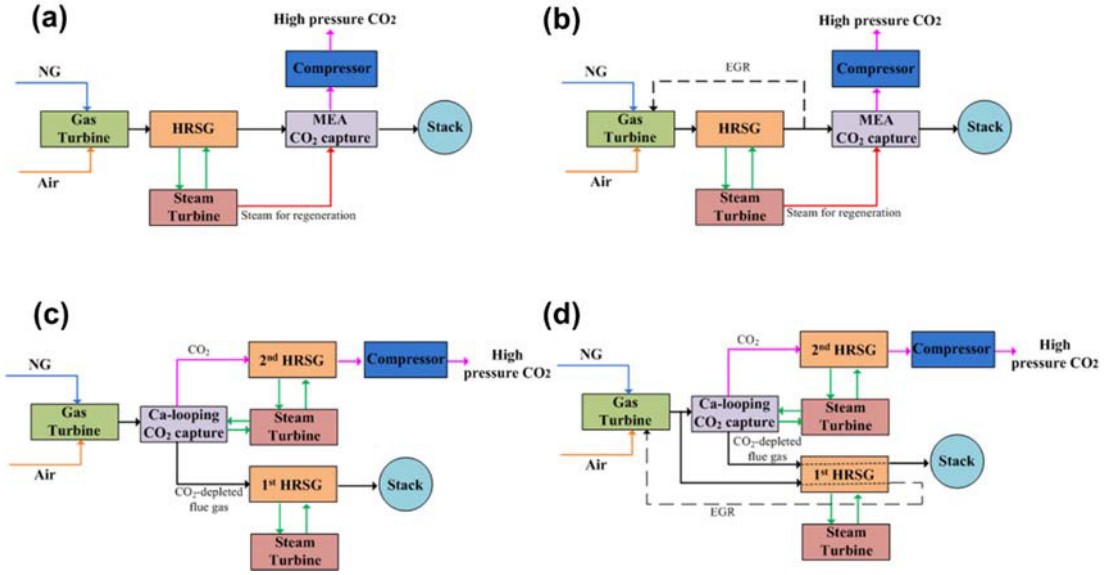

Fig. 1. Block flow diagrams of NGCCs integrated with carbon capture: (a) NGCC+MEA; (b) NGCC/EGR+MEA; (c) NGCC+Ca-looping; (d) NGCC/EGR+Ca-looping.

4. Economic analysis

The economic evaluation results of all cases are summarized in Table 2. Even though a Ca-looping unit alone was by large less costly than an amine capture unit, the overall plant TPC was greater in Case 3 than in Case 1. This is mainly due to Ca-looping capture cases requiring additional HRSG and steam cycle for heat recovery from the Ca-looping unit. The variable O&M cost also increased significantly due to additional fuel consumption at the calciner. All in all more natural gas is to be consumed for Ca-looping cases than for amine cases, resulting in the CO_2 product flowrate increasing. Accordingly, the CO_2 compression unit becomes larger. However, such negative effects were offset by increased net power outputs in Ca-looping capture cases. It turned out that the NGCC power plant could be decarbonized more economically by a Ca-looping capture unit with respect to both cost of electricity (COE) and cost of avoided CO_2 (COA). By incorporating the EGR, the size of a capture unit could be reduced since the flowrate of the flue gas flowing to the capture unit would decrease more or less in proportion to the fraction of the flue gas being recycled. More importantly, implementing the EGR led to less fuel being consumed at the calciner, reducing the variable O&M cost as well.

Table 2. Estimation of capital costs and COE (2015 base).

Process description		Base case NGCC	Case 1 NGCC + MEA	Case 2 NGCC/EGR + MEA	Case 3 NGCC + Ca-looping	Case 4 NGCC/EGR + Ca-looping
Feed water system	M$	44.53	49.08	49.89	100.88	85.70
CO2 recovery system	M$	——	228.85	161.23	137.26	96.70
CO2 compression unit	M$	——	25.85	25.64	42.27	38.20
Gas turbine cycle	M$	103.32	103.32	103.32	103.32	103.32
HRSG system	M$	51.53	51.53	52.42	68.99	69.81
Steam turbine	M$	54.02	44.29	45.27	119.08	107.48
Cooling water system	M$	17.93	26.91	26.91	26.91	26.91
Accessory electric plant	M$	36.81	48.63	45.12	100.71	85.28
Instrumentation & control	M$	14.30	16.23	15.13	32.12	27.49
Improvement to site	M$	10.02	10.03	10.02	13.01	12.34
Building & Structure	M$	11.29	10.68	10.67	12.89	12.40
EGR system	M$	——	——	15.30	——	15.30
TPC	M$	343.75	615.40	560.93	757.45	680.92
Owner's cost	M$	78.35	136.47	125.13	179.37	163.42
TOC	M$	422.10	751.86	686.06	936.81	844.34
Specific investment cost*	USD/kW	741.71	1527.87	1386.26	1160.72	1150.48
Fixed O&M cost	M$	12.93	21.76	20.12	26.02	23.72
Variable O&M cost	M$	201.05	205.66	205.01	360.56	319.17
COE	USD/MWh	60.95	88.04	84.96	84.83	83.10
COA	USD/t CO_2	——	85.43	76.34	72.25	67.51

* TOC/net power generation

5. Conclusions

In this study, the operating conditions of a Ca-looping process were tailored for its application to a NGCC flue gas and the energy penalty involved was estimated accurately by process simulation. By increasing the CO_2 mole fraction in the flue gas by exhaust gas recirculation, the Ca-looping process could be operated at more favourable conditions, such as higher carbonation temperature and less circulating solid flowrate, resulting in less fuel consumption at the calciner, greater power generation at the primary HRSG and its associated steam cycle and higher CO_2 product purity. In conclusion, it is essential to implement exhaust gas recirculation to a NGCC for its efficient process integration with a Ca-looping process for post-combustion carbon capture.

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Biography

Yue Hu is currently a PhD student in School of Energy Power and Mechanical Engineering, North China Electric Power University. The main research field is process design and optimisation of energy-efficient power plants integrated with CO_2 capture.